Defense Technical Information Center
Compilation Part Notice

ADP014087

TITLE: The Need for a Systems Engineering Approach for Measuring and Predicting the Degradation of Aging Systems and How It Can Be Achieved

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Ageing Mechanisms and Control. Specialists' Meeting on Life Management Techniques for Ageing Air Vehicles [Les mecanismes vieillissants et le controle] [Reunions des specialistes des techniques de gestion du cycle de vie pour vehicules aeriens vieillissants]

To order the complete compilation report, use: ADA415672

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP014058 thru ADP014091

The Need for a Systems Engineering Approach for Measuring and Predicting the Degradation of Aging Systems and How It Can Be Achieved

William Robinson
Gisele Welch
Gary O'Neill
Georgia Tech Research Institute
Logistics and Maintenance Applied Research Center
925 Dalney St
Atlanta, Georgia 30332-0834
USA

1.0   Introduction

This paper will explore the need for a comprehensive approach to measuring, and predicting, degradations in aging NATO aircraft and use of these predictions in a 'systems approach' to solving the challenges faced in supporting these aircraft. Various groups within the NATO countries have already accomplished significant progress in this area, so this paper is an attempt to refine a more global process that will provide the most useful results in the least amount of time. We believe that the appropriate application of both emerging and seemingly unrelated technologies, coupled with a systems engineering management approach, may provide acceptable results.

2.0   Defining the Real Problem(s)

As stated in the theme for this meeting, the problem being addressed is aging aircraft and how to best minimize the effect this situation has on NATO countries. This is the ultimate, high visibility, problem to be solved. In reality, though, the 'Aging Aircraft Problem' is a series of smaller scale, inter-related issues. This reality demands that a 'systems approach' be used to formulate the specifics of the problem and define the successful path to resolve those issues.

The more complex problem facing NATO is how does a team of countries work together to develop a program that allows the inter-related problem elements to be solved in an effective manner that provides each country with measurable results in lowering the burden of repairing and maintaining an aging fleet. At the heart of this problem is the need to understand the degradation processes involved and the need to predict the future effects of degradation in a cohesive manner that provides effective insight to the potential solutions.

Managers in organizations, such as NATO, that are forced to deal with the problems associated with aging systems must not only focus on solutions; but also determine how to implement a process that will provide solutions in the manner which achieves a cost effective solution while maintaining necessary operational capability. Total success is unlikely. Optimizing the return (safety, availability, minimized operational costs, mission capability) on investment (funding, personnel, time, political posture) is the best that can be accomplished and should be the goal. The reality of the situation is that there is more "return" needed than there is

"investment" available. It is the manager's job to attempt to provide a balanced solution to optimize return on investment.

3.0   Systems Engineering

The development and use of the systems engineering process for military development programs, began in the mid-1950s on ballistic missile development programs, and expanded world wide through the 1960's. Programs that benefit the most from a systems engineering approach are typified by the following characteristics;

- Large teams are needed to develop the solution or system.
- Personnel resources are highly specialized.
- Many different organizations are involved.
- Participating Contractors and Government organizations are located throughout the country or world; making communications, coordination, and interfacing difficult..
- Many related problem elements are being solved concurrently.
- Operational and logistic support requirements are very complex.
- Time to develop a solution or product is constrained.
- Solutions are dependent on the successful transitioning of advanced technologies.

Systems engineering is both a technical process and a management process. Systems engineering is a methodology or process by which expert knowledge is applied to:

- Transform an operational need into a description of the system performance parameters (commonly known as requirements).
- Development of a system configuration that will achieve performance parameters.
- Integrate related parameters and insure compatibility of all physical, functional, and program interfaces in a manner that optimizes total system performance compliance.

Since most of this audience is made of individuals working directly in the aerospace industry or closely related areas, you will be or have been involved with the systems engineering approach for development of aircraft or aircraft sub-systems.

Traditionally, the systems engineering process has been applied to technical development programs in which a hardware or software system was being developed. However, we are proposing that this methodology might also be successfully applied to the development and optimization of the system, or model, for predicting the future effects of degradation. The characteristics of a solution to the NATO Aging Aircraft problem match the characteristics listed above and like most development programs these days, also involves international politics, budgetary constraints, and limited personnel resources. In short, this is a 'textbook example' of a challenge that would benefit from Systems Engineering Processes.

4.0   Basic Systems Engineering Process

Without a flexible, but rigorous approach to solving a complex problem, funds, time, and personnel can be wasted either by solving the "wrong" problem, developing an incomplete solution, or over-developing a good solution. Since the parameters that affect the problem definition are often dynamic in the real world, we need a process that is adaptable to changing

requirements, yet structured in a way that minimizes lost effort. The systems engineering process uses the following structure:

(a) Define the requirements or needs that the solution should fulfill
- Define end-user requirements (top-level global requirements)
- Perform functional analysis to divide top-level requirements into smaller elements and to determine alternate means of achieving the top-level requirements.
- Define the inter-relationship between the requirements, if possible.
(b) Develop concept designs or plans that will satisfy the requirements.
(c) Evaluate the proposed concepts and decide on most promising approach(s)
- Perform trade studies to identify weaknesses and risks
- Evaluate and optimize to eliminate weaknesses and minimize risks
- Quantify compliance of concepts relative to top-level requirements
- Chose 1-3 concepts to more fully develop ·
(d) Fully develop the concept(s) chosen in the previous step.
(e) Verify that the system or program meets the top-level requirements.

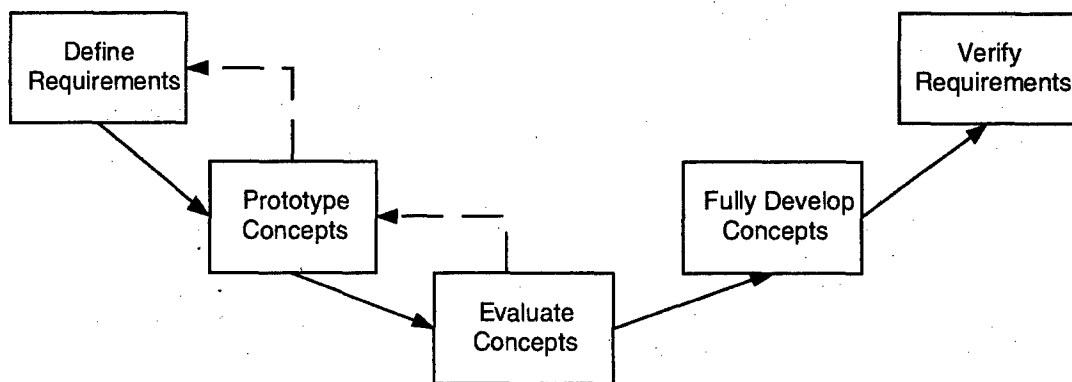Steps (a) through (c) are iterative as shown in the diagram of Figure 1.

Figure 1. The Systems Engineering Approach

Most people and organizations developing new products and solving day-to-day problems use the above process, or a modified version of it, because it is a natural process to follow. What is sometimes lacking is a disciplined and systematic framework for quantifying and documenting the various steps, resulting in a less structured process that allows the results to be influenced by chance, limited or irrelevant knowledge and experience, intuition, or other factors.

5.0   Top-level Requirements

A rigorous systems engineering process will provide acceptable results in meeting technical requirements. We must also realize that there are other non-technical requirements that can be ultimately more important because they often decide the perception or degree of success or failure of the project by other stakeholders, such as the legislature or public opinion

As stated by others working on the aging aircraft problems over the past 5-7 years, examples of the top-level requirements that pertain to the aging aircraft problem are shown in Figure 2. We have added two requirements that are often missing from the requirements list: (a)

time given to "solve" the problem and (b) funding available to "solve" the problem. These last two requirements are the most important for those managing the process that will develop a solution.

Top-Level 'System' Requirements
Maintain Flight Safety Extend Aircraft Service Life Maintain or Increase Aircraft Availability Maintain Mission Capability Reduce or Constrain Total Operating Cost Permit Sub-system Moderation Cost of Improvement Program Minimum Impact on Aircraft Availability

Figure 2. Top-level Aging Aircraft requirements

All requirements, whether top-level or those that are derived from the top-level requirements, must be verifiable either through analysis, test, or a combination. Examples of verifiable requirements might include: Accident rate of less than 1 aircraft loss per 100,000 flight hours: Availability greater than 90%; FMC rates above 90%; and growth in cost of ownership less than some baseline amount.

6.0   Modeling the Aging Aircraft System

The aging aircraft system can be modeled using a three tier modeling architecture, as shown schematically in Figures 3 and 4. The quantifiable outputs of the top-level model will be used to determine compliance with the top-level requirements discussed in Section 5.0.

The next lower level of model development would represent the sub-systems and components of the aircraft in terms of their contributions to the high level quantities. As examples, the second tier models might address; how engine failures affect the accident rate, availability and FMC rates; how does maintenance on the system affect availability, FMC, and ownership cost.
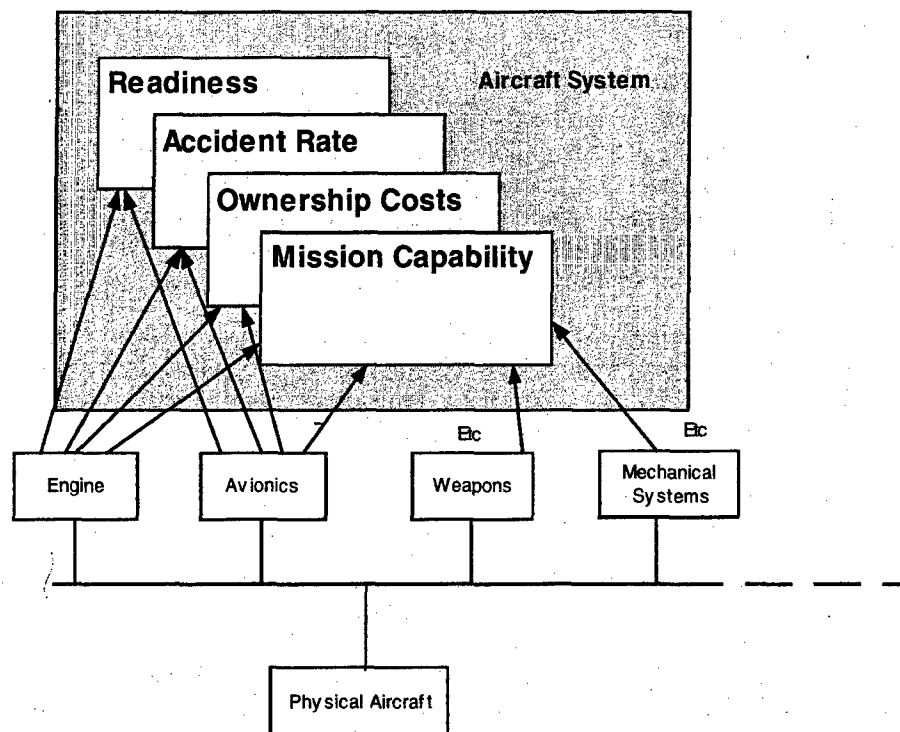
Figure 3: Aircraft System and Sub-System Models

The third level of this systems model would represent the effects of operation (including changes to original employment assumptions), age related damage mechanisms and other failure mechanisms (improper maintenance, non standard material, etc) and how these relate to the aircraft sub-systems and components
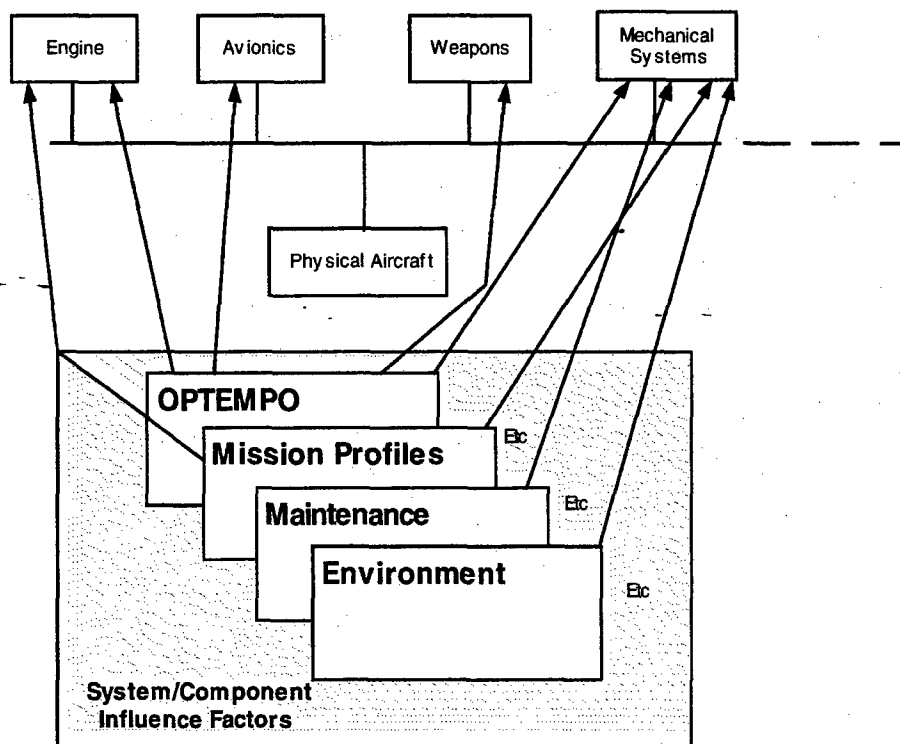
Figure 4: Tier Three Models

7.0   Functional Analysis

The 3-tiered model above will provide a powerful tool for analyzing the optimum 'system' configuration and where improvements need to be made in order to meet the top-level requirements. By using this architecture to flow requirements down to the third level and by flowing capabilities up to the top-level, an iterative process can be developed that will identify weak areas that need improvement. This type of modeling can also be used to perform sensitivity analysis to determine where the most return on investment can be realized, where technology insertion may have the biggest benefits, and to help identify and quantify risk.

The lowest tier of the model above is intended to describe damage mechanisms that degrade the system or component level operation of the aircraft. From these descriptions, a prediction of the effect on the aircraft as a total system can be forecast. From this forecast, the damage mechanisms that contribute to the greatest degradation of the aircraft as a system can be ¯ assessed. From that assessment, decisions as to what actions to take with respect to those mechanisms can be optimized: Just as with human health, the treatment for various factors attacking an aircraft can be balanced when taken together as a whole.

Once the individual models are developed and validated in each of the two lower tiers, the top-level model can be assembled and validated, by combining the elements according to their inter-relationships. After validation of the top-level model, it can be used with a range of statistically valid input parameters for the lower tiers that relate to the "real-world" and the range of results can be analyzed. From the analysis, a decision can be made, selecting the combination that achieves the best mix of desired outcomes. The result is a set of requirements, each of which has a quantifiable range of acceptable values.

From this set of balanced requirements, a set of concepts can be developed which address the requirements. For example, if reducing the amount of stress corrosion cracking is deemed necessary to raise the availability and lower the maintenance manhours of a particular aircraft, then several concepts which are focused on stress corrosion cracking could be developed and tested, with the most effective means chosen on the basis of defined metrics.

As the systems engineering process continues, the models developed during the functional analysis phase will become very important in quantifying and minimizing risk, and optimizing return on investment. The solutions chosen will be more credible and justifiable because they were obtained in a rigorous manner based on facts are quantifiable and were validated with knowledge and experience. Other important values that arise from the development of these models are: the ability to quickly review the effects of changes that may occur over time, and the ability to modify the overall design to meet the influences of a dynamic world.

8.0   Prediction of Damage Mechanism's Impact on the Aircraft as a System

As we've discussed above, the proposed 3-tiered model contains the effects of damage mechanisms at its lowest tier. To provide meaningful results for the high level model of aircraft characteristics, the lower tiers must have comprehensive, high fidelity quantities serving as input parameters. High fidelity models are usually the fastest and least expensive tools for predicting future degradation rates under various influential parameters.

Therefore, the key to understanding the overall issues regarding aging aircraft is to first understand the lower level parameters. The first element is the present condition of the fleet. Next, we must analyze the rate of degradation under various realistic situations, and then assess the extent of the problem if the degradation is left unchecked. Once the problem is defined in terms of meaningful quantities versus time, concepts can be developed and implemented to slow-down or arrest the degradation. Modeling the degradation mechanisms also permits sensitivity analyses to be performed, which will demonstrate the parameters having the largest effect on degradation, guiding the selection of the parameters that need the highest priority for solution.

The two dominant areas that require the most attention for aging aircraft are structural degradation due to corrosion enhanced cracking and electrical power or signal wiring degradation, due to insulation/shielding failure and conductor open-circuit failure. Both of these problems are expensive and time consuming to fix. So it is important to understand the present extent of degradation and apply modeling techniques to determine the rate of degradation.

To determine the best modeling approach for degradation prediction of NATO aircraft affected by structural corrosion damage, the following process should be considered:

- Develop database that includes NATO inventory information.
- Add historical corrosion information to database.
- Develop "Repair Priorities Algorithm" to determine initial priorities for repair,
- Add information on corrosion measurement techniques to database.
- Perform corrosion degradation measurements to establish corrosion baseline, and add corrosion measurement data to database.
- Using corrosion data, develop a "Corrosion Degradation Model" to predict future corrosion related degradation.
- Update corrosion prediction algorithm to determine optimum measurements to use on highest priority aircraft and locations.
- Use predictions to help modify/define top-level requirements, funding efforts, and future plans.

This process is dynamic and may require iteration as new knowledge is gained. This process is shown graphically in Figure 5.
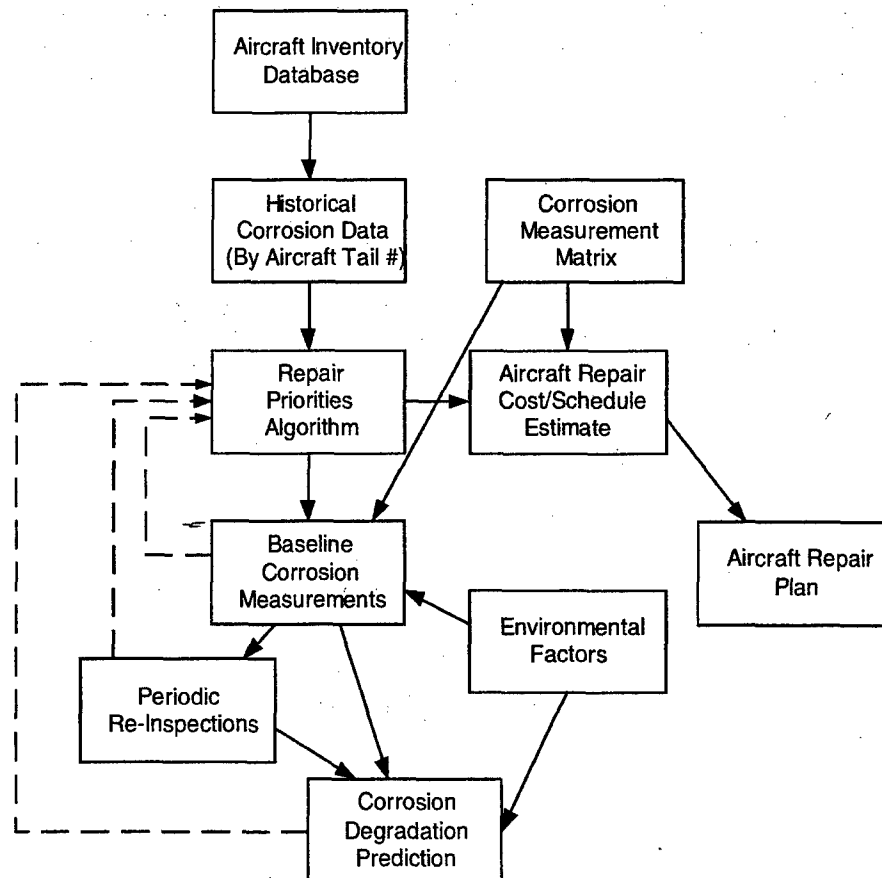

Figure 5. Measurement and Prediction Process

Each block in the diagram will be discussed in the sections that follow.

9.0   NATO Inventory Information

First, a database containing the various types of NATO aircraft must be established. The database should contain the number of each type of aircraft in service, aircraft manufacturer, countries owning the aircraft, and any other information that might be pertinent to later decisions regarding which aircraft should be repaired and the repair timeline. Such a database probably already exists in some form, but probably does not contain all the needed information to develop a useful algorithm to determine optimum deployment of resources for the task of repairing structural corrosion damage.

It is also important to begin establishing realistic funding profiles for repair of each type of aircraft. While current funding profiles may have been previously generated based on incorrect or non-applicable assumptions, starting with these projected funding amounts and timelines is helpful as an initial baseline. As the rest of the process is completed and iterated, each nation and NATO as a whole may see how changes and redistribution in the funding might produce better overall results.

10.0   Corrosion History Information

Previous inspection and repair records, other relevant maintenance history, structural susceptibility information, and environmental data, along with any other structural or corrosion related information that might add to the knowledge base should be added to the database for each tail number. Just as previous funding timelines are useful as a baseline, past technical information may also be of some help in establishing a baseline of the condition of the aircraft, even if it contains some small fraction of incorrect data.

Care must be taken to strive for consistency of format and accuracy for this information. The existing data may be in different formats for the same types of aircraft and from nation to nation, or vary from aircraft type to type. The amount and usefulness of the data to an overall model must be carefully assessed. Extreme caution should be used when trying to rely on previous data to indicate the degree of corrosion degradation or extrapolating the rate of degradation. The cost of obtaining and reformatting this data should be analyzed, as it may be too expensive to make it worthwhile in some limited cases.

11.0   Repair Priorities Algorithm

Using the information in the database along with expert knowledge, an algorithm can be developed to help determine the priorities with regard to which aircraft and which structural damage type should be given highest priority. This algorithm will be called the Repair Priorities Algorithm. The algorithm developed for this analysis must take into consideration all of the important aspects of the issues previously stated in Figure 2. In addition, the algorithm must take into consideration the time line of degradation, estimated repair cost and schedule, and overall funding profiles.

12.0 Environmental Factors

The environment plays a key role in all aging aircraft related damage mechanisms. Duration of exposure to high humidity salt air, sand, heat and corrosive gases are examples of factors that influence the aging process. Exposure histories of individual aircraft, as well as algorithms based on fleetwide experience are essential to damage prediction.

13.0 Corrosion Measurement Techniques

Many different types of corrosion detection and measurement techniques have been developed over the last 5-10 years. Many of the techniques used today were originally developed for detecting and measuring other types of structural flaws and have been modified to address the peculiarities of corrosion and corrosion-induced failures. No technique works well in all situations; but for almost every measurement condition, an accepted technique is optimum. Researchers in the various NATO countries are developing new measurement techniques and these new techniques need to be reviewed, tested, and compared with the older techniques and with future measurement objectives. Not only is measurement accuracy important, low false data rate, speed of measurement, and costs of measurement are important factors in the overall model.

Once the aircraft types and corrosion problem areas have been prioritized, a matrix of measurement techniques applicable to each type of aircraft and problem area can be created and added to the database. The measurement information should include effectiveness, performance time, and cost metrics that can be used to determine the most effective measurement techniques to use for each problem area. Adding this measurement information to the database will guide the choice of the best corrosion measurement process to align with the results of the Repair Priorities Algorithm. This combination will provide useful cost data for the measurement process needed to support the plans that result from the Repair Priorities Algorithm.

14.0 Corrosion Degradation Measurements

Having derived the most pressing corrosion priorities and the best measurement for assessment of system degradation, a plan to develop fleet baseline data and periodic updates of degradation can be developed with participation, at some level, by all NATO countries. In addition to serving as a technical measurement guide, the plan is useful as a management tool. The measurement plan should include a recommended data formats, calibration techniques, and other technical information needed to produce data that is both technically useful, consistent, and tailored for improving the Repair Priorities Algorithm.

As new corrosion measurements are taken, the data should be periodically added to the database. Management of the data and database should be addressed in the measurement plan. The plan should address what data should be taken, the format of the input data, where it will reside, who will input data to the database, how data will be input, who will be responsible for management of the database, and how the database management will get funded.

Management of the database, while important, is not the primary goal here and should not be an excuse to generate a bureaucracy. If designed properly, it should be easy to input data, easy to manage the data, and user friendly for both the field personnel collecting the data and the algorithm developers using the data.

15.0   Initial Model to Predict Corrosion Related Degradation

As the new data is added, the Repair Priorities Algorithm should also be periodically updated and re-calculated to confirm or modify the measurement approach, measurement funding priorities, and the usefulness of the data being captured.

In addition to updating the Repair Priorities Algorithm, a new model should be developed that takes into consideration the baseline corrosion degradation and predicts how the corrosion and related structural problems will change with time. We will call this new model the "NATO Corrosion Degradation Model". A number of people/organizations are working on similar models or parts of this model. However, to my knowledge, no one has tailored a corrosion degradation model to the NATO aging aircraft fleet.

Among the model's input parameters will be the corrosion degradation measurements being made under the measurement plan, effectiveness of repair actions, effectiveness of operational changes, and effects due to changes in mission. The model will allow the user to determine how the level and rate of degradation is affected by varying the input parameters, thus allowing the parameters to be optimized and allowing sensitivity analysis to be made for the various input parameters.

As a side note, one of the important technology areas that has been pursued in recent years is to develop techniques and processes to provide accelerated corrosion degradation under controlled conditions. These techniques may provide an important tool in the development of degradation models, if the techniques can be proven to be reliable.

16.0   Update Corrosion Prediction Model

Just as with the Repair Priorities Algorithm, the NATO Corrosion Degradation Model should be reviewed and updated as more knowledge is gained about the corrosion process and how it is influenced by various parameters. Again, as with the measurement database management plan, management and upgrade of this model is an enabling goal, not the ultimate goal; which is to fix the problem. So, the model should be developed just to the level required to give the answers needed to fix the problem.

17.0   Wiring Degradation Modeling Process

A process similar to the one outlined above for corrosion should be constructed for the other dominant aging mechanism: aircraft wiring degradation. Beginning with the aircraft inventory database, historical data on wiring degradation and inspection techniques, a Wiring Improvement Algorithm can be developed to determine the best approach to solve the wiring issues on an aircraft type basis. Once the repair priorities are established, a measurement plan to assess the baseline condition of the aircraft can be updated with periodic re-inspections. From that process, a refined degradation prediction model can be developed, and updated in the same way as the corrosion prediction model.

It may be useful to develop both prediction processes in parallel, to minimize the out of service time of the aircraft during baseline inspections and repair.

18.0   Developing the Concepts

Once models are in place and validated, various concepts (designs) can be developed to satisfy the requirements. Once a concept has enough structure and definition, it can be modeled and evaluated using the same process that developed the overall model. Trade studies can be made during this phase, risks identified, and risk assessments made. Evaluation of the concepts will indicate if the requirements can be met, or the existence of any shortfalls. . If the concept produces results below the requirement, the concept can perhaps be modified to increase the capability. If the evaluations show more capability than needed to satisfy a requirement, perhaps the concept can be modified to decrease its capability by decreasing cost, time, personnel resources, or other factors.

When all of the concepts have been evaluated and the degree of compliance established for each concept, a decision can be made on how to proceed with further concept development. Depending on funding, time availability, and other issues, more than one concept may be taken to the next level of analysis or implementation. It is unlikely that all concepts will meet all the requirements equally. Usually, the decision to proceed with a concept is straightforward. In many cases only one concept plan should be developed. If none of the concept plans meet the requirements, the project should be dropped, the requirements re-analyzed, or more clever people should be employed.

19.0   Development of the Plan(s)

After selecting the best concept(s), based on quantifiable requirements and capabilities, a plan of action and milestones to develop and implement testing of the concept(s) can be written to whatever level is required for successful proof. As with any complex plan or program, the work should be reviewed periodically to insure all resources are being applied to completing the plan(s) and that all elements of the team are working toward the same goals.

In any dynamic environment, the plan(s) may require modification as requirements change, as resources change, or as second-order problems arise during detailed development. While these changes are a nuisance and sometimes frustrating to deal with, the previous modeling of requirements and capabilities will at least allow the program managers to understand the effects of the changes and how to optimize the outcome. These tools will often allow the program managers to better justify requests why more funding might be needed, the impact of potential funding cuts or program time slips.

20.0   Validation of the Final Concept Implementation Plan

Prior to full implementation of the proven concept, a "sanity check" should be made on the plan to insure it agrees with past experience and knowledge. Management should review the plan. This would be the equivalent of a Critical Design Review (CDR) for equipment or software development programs.

21.0   Summary

This paper has attempted to show how a systems engineering methodology can help program managers from different NATO nations work together to develop measurement and prediction models that can be used to optimize financial and personnel resources in the quest to

satisfy adequate operating requirements for the aging NATO fleet. The object of this approach is to keep management focused and coordinated on the end goals (top level requirements) and the process that will optimize the trip from the present situation to attainment of the goals.

It must be stressed that the systems engineering methodology provides tools that will allow reasonable requirements to be defined in a verifiable, quantifiable manner. The authors believe that it is far worse to have requirements that are too stringent, than to have requirements that are slightly lax. Requirements that have been arbitrarily set too high due to lack of knowledge or lack of test data will waste financial and personnel resources and this waste can never be recovered. Any safety margins or "padding" put into a requirement must be based on variances that can be proven as a result of test results or rigorous analysis.